SENSITIVITY ANALYSIS OF THE THREE STRATA FIRE MODEL : IMPLICATIONS FOR FIELD SAMPLING ACCURACIES

GRADIENT MODELING, INC.

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THREE STRATA FIRE MODEL :

IMPLICATIONS FOR FIELD SAMPLING ACCURACIES

by

Collin D. Bevins
Research Supervisor

and

Merideth W. Potter
Systems Consultant

Gradient Modeling, Inc.
Missoula Office
Box 2666
Missoula, Montana 59801

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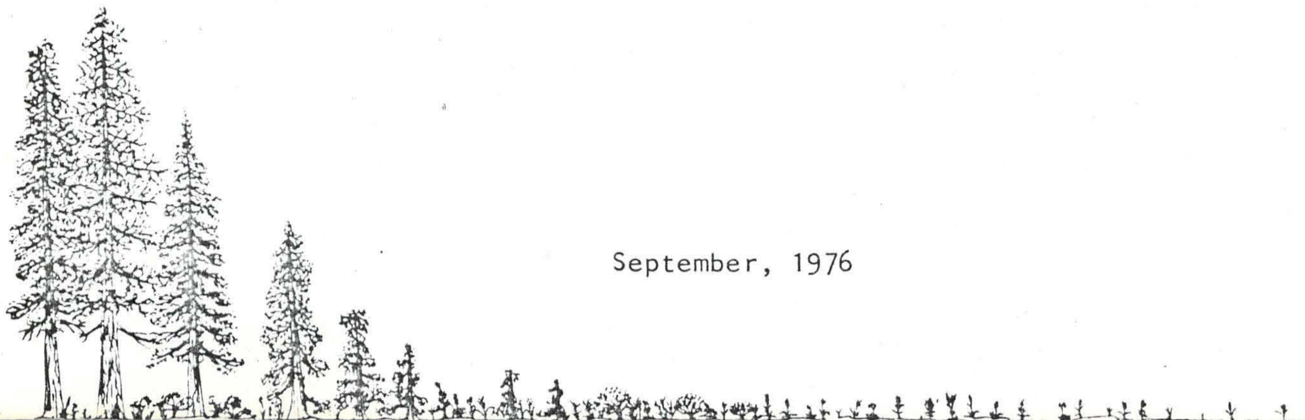

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INTRODUCTION

In 1972, a theoretically-based and empirically-derived fire spread and intensity model was developed at the USDA Forest Service's Northern Forest Fire Laboratory for estimating the potential behavior characteristics of free-burning fires in natural fuels (Rothermel 1972). This model has been widely used, both directly in predicting real-time fire behavior (Kessell 1976) and indirectly in evaluating relative fire danger (Deeming, et al. 1972). The model serves as the integrator of many fire parameters, including wind, slope, fuel load, fuel moisture, array packing ratio, and the physical properties of the fuel (Table 1).

To use the fire model in evaluating fire danger, fuel hazard, and/or fire behavior on a management land unit, the manager must supply the necessary data inputs on wind and fuel moisture, arrangement, and quantity by fuel particle size class. A sensitivity analysis of the Rothermel model has been performed on the model's response to its various inputs (Sanderlin 1975). While this study has addressed the sensitivity question with respect to the model's testing and development, a major question still remains when applying the model in the field; how accurate must the manager be in assessing the model's input parameters to achieve a desired level of prediction resolution and error tolerance? This question implies not only a concern for the fire model's sensitivity and accuracy *per se*, but also for the accuracy of the inventory techniques used and the resulting demands on his time, manpower, and economic resources.

OBJECTIVE

It is the objective of this analysis to demonstrate an approach to answering this question of concern at the field office level. This will be accomplished by determining the level of accuracy or resolution required in measuring the necessary fire model parameters in the field (i.e. sampling error tolerances) to remain within a specified error in the resulting fire behavior predictions. These parameters include the windspeed at midflame height, terrain slope, and fuel array loads, moisture contents, and packing ratios.

Due to the complex nature of many of the model's intermediate relationships, its sensitivity to an absolute change in a given parameter value is highly dependent upon that parameter's initial value. For this reason, twelve hypothetical fuel models were examined for the absolute change in their parameter values allowable and maintain the resulting fire behavior prediction change within an acceptable level.

The Three-Strata Fire Model

The Rothermel fire model is based upon empirical relationships between measurable, static fuel-environmental properties and the resulting dynamic fire behavior. To establish these relationships, homogeneous and continuous fuel beds of uniformly-sized particles were burned under laboratory-controlled environmental conditions. While allowing the elucidation of fire effects relationships, the approach resulted in a model that accepts only single parameter values representing heterogeneous fuel arrays. For example, only a single number is used for the fuel load

in the model's calculations, a number that must somehow realistically represent the diverse fuel situation of concern. A weighting system was derived to mathematically reduce the model's parameter distributions into single, representative values. Under the observation that fire spread rate tends to be a function of fuel surface area, Rothermel (1972) suggests a weighting factor determined by each fuel component's surface area contribution to the surface area of the entire array. Thus smaller fuels with higher surface-area-to-volume ratios tend to control the fire model's predictions more than the larger fuels.

Two assumptions inherent in the fire model's development are of concern when applying it to complex and diverse natural fuel situations. First, the model assumes the fuel array to be uniform, homogeneous, and continuous in three dimensions. Second, the method of weighting parameter values for each fuel component mathematically produces acceptable fire behavior predictions.

To lessen the consequences of, and conform more closely to, these two assumptions, the original fire model and its recent improvements (Albini 1975) has been adapted for more realistic application in natural fuels (Bevins 1976). Studies on fuel distributions in Glacier National Park show natural fuels not to be uniform, continuous, or homogeneous vertically. A vertical profile of these arrays shows a tendency towards the formation of three distinct vertical fuel-vegetation strata. Within each of these stratum, the fire model's assumptions are more closely approximated. The lowest level of the three is the compacted duff and litter layer atop the mineral soil. The second stratum consists of the

grasses, non-woody herbs, and fallen branchwood that lay on top or are supported above the litter. The third stratum is the supported, woody-stemmed vegetation and shrub layer up to about 2.0 meters in height.

The strata adaptation of the fire model assumes the fire will travel through that fuel-vegetation stratum which is most flammable or susceptible to the highest spread rate under the existing environmental conditions. While the fire front travels first and fastest through this optimum stratum, it may also serve as an ignition source to the other two strata.

This approach assumes the leading edge of the combustion zone will spread through the optimum stratum dependent upon that stratum's burning characteristics alone. That is, the optimum rate of fire spread and the flame length at the leading edge of the combustion zone is determined by that single stratum's reaction intensity, independent of the reaction intensities or heat sinks of the other two strata. It is furthermore assumed this stratum will ignite the other two strata, which will then burn according to their characteristics. Therefore, fire spread rate and flame length is based upon the rate and intensity of the optimum stratum, and fireline intensity is the product of this spread rate and the sums of the products of the individual stratums' reaction intensities and residence times. This total fireline intensity is then used in subsequent scorch height and torch height equations.

The strata model allows for a prediction of the stratum through which a fire is most likely to spread, and may serve as a means for defining "blow-up" conditions in shrubby or "fluffed" activity fuels. Furthermore, since wind and slope interactions have differential effects upon

the various fuel layers, the strata approach may yield an approximation of fire perimeter growth (and associated fire behavior characteristics about the perimeter) when coupled with a wind-slope vector analysis. This introduces the capability of predicting an ellipse-like fire perimeter whose front is rapidly advancing through the shrubs, flanking through the dead and down layer, and backing through the litter.

But most importantly, the strata adaptation partially overcomes the limiting assumption of vertical continuity by realistically modeling the natural fuel array as three strata, each with distinct array characteristics. By dividing the total fuel complex into three parts and evaluating each one separately, there tends to be fewer components in each layer than in the whole, reducing some of the unknown effects of the model's surface area weighting method.

To reflect the impact of large accumulations of fuels larger than 7.62 cm in diameter on the total fireline intensity and scorch height, they are included in the surface area weighting procedure. While the inclusion of these fuels may slightly reduce the predicted spread rate, the fire's residence time is increased, and thus also the fireline intensity.

Because of the strata model's special applicability to natural fuel conditions, it was the fire model version tested in the sensitivity analysis.

METHODS

To carry out this analysis it was necessary to predetermine (1) the input parameters to be tested, (2) the initial values of the parameters, (3) the fire behavior characteristic(s) against which the parameter changes are evaluated and (4) the magnitude of change in the fire behavior importance variables to be affected by the parameters.

The input parameters tested are those which must be measured in the field by inventory crews or fire weather observers (Table 2). These include the fuel loads and moisture contents by fuel size class, fuel strata packing ratios, windspeed at midflame height, and terrain slope.

Untested parameters are those whose values can be determined in the laboratory and whose assessment is not of concern to field inventory crews. These include the fuel components' low heats of combustion, surface-area-to-volume ratios, particle densities, total mineral contents, effective (silica-free) mineral contents, and the moisture of extinction for each stratum. The constant values used for these parameters in the analysis are given in Table 3.

As previously mentioned, the sensitivity of the fire model's outputs to changes in its parameter values is dependent upon the parameter's initial value, e.g., most of the model's functions are non-linear. This creates the problem where the range manager needs a different level of inventory resolution for grass fuel loads than does the forest manager. To overcome this limitation, twelve hypothetical fuel conditions were created

to represent the entire spectrum of fuel situations that might be encountered in the field (Table 2).

The use of these hypothetical fuel models proved useful in several respects. First, each model is a mathematical progression of the previous one. This progression benefits the analysis of results such that trends in sensitivities to a single parameter type can be more easily distinguished through the progressive series of fuel models. Second, the hypothetical models are representative of real-world fuel conditions (Bevins and Jeske 1976), and serve as discrete points along a loosely defined fuel continuum. Models 1 through 4, for example, can be viewed as a cover type or primary succession progression from grasslands to savannahs or krummholz to young forest. Models 3 through 12 may represent the accumulation of natural fuels in a stand through time, or the progression in fuel conditions between stands from vigorous fifty-year lodgepole to decadent western hemlock/Douglas-fir. Alternatively, Models 3 through 12 may also be viewed as a single stand subjected to more rigorous levels of treatment, such as harvest, blowdown, or insect attack. Basically, it was felt this selected range of fuel conditions could find application to any manager's fuel concerns.

The fuel particle components tested include the litter, grasses and herbs, fallen branchwood in four size classes, and shrub foliage and stemwood. Each component follows a function from Model 1 to 12 based upon data from Glacier National Park (Bevins and Jeske 1976). Litter loads are constant at 5.0 T/ha through Model 7 where it begins to accumulate at a rate of 1.0 T/ha/model. Grass and herb loads start out high

at 5.0 T/ha and drop by 1.0 T/ha/model to Model 4 where it remains constant at 2.0 T/ha. Branchwood accumulates beginning at Models 2 and 3 at the rates of 0.5, 1.0, 2.0, and 10.0 T/ha/model for the 0.0-.64 cm, .65-2.54 cm, 2.55-7.62 cm, and >7.62 cm sized fuels, respectively. Shrub foliage increases from 0.0 to 6.0 T/ha through Model 7, and then declines by 1.0 T/ha/model. Shrub branchwood loads are taken as the square of the foliage loads.

The litter packing ratio is considered constant for all the models under the assumption that 1.0 and 10.0 T/ha of needle fall have the same bulk density. The packing ratio of the second stratum is based upon a constant fuel depth for all fuel models of about 20 cm. The change in the packing ratio from model to model is therefore a consequence of the change in total loading of the fuels less than 7.62 cm in diameter. The shrub stratum packing ratio reflects a depth of 25 cm for Models 1 and 12 where shrub loads are low, and a depth of 50 cm for the other models. Since this layer lies atop the 20 cm deep dead and down stratum, it reflects a shrub height of 45 to 70 cm.

The windspeed at midflame height used was 2.0 mi/h. This is the windspeed which actually affects the fire in the fuel array, and corresponds to a 5 to 15 mi/h wind at 20 feet, depending upon canopy cover and terrain. Finally, a slope of 10 degrees (17.6%) was chosen as nominal to most areas in the western U.S.

Fuel moisture values selected represent the average weather day from the pine savannahs of western Glacier National Park over its 100 day fire season for the past 15 years. This was used rather than an "average worst"

day to minimize the possibility of fuel moisture values dropping to 0% during the sensitivity analysis without affecting the desired change in predicted fire behavior. The fuel moisture values used are listed in Table 2.

A computer program was written to perform the tedious work involved in the analysis (SANAL). This program takes the initial values of a fuel model and uses the strata fire model to compute nine baseline fire variable values. These include the rates of spread and flame lengths for each stratum, the maximum rate of spread (R_{max}), the total fireline intensity (I_B), and VanWagner's (1973) scorch height (SH3). The baseline values for the twelve fuel models under initial conditions are summarized in Table 4. The program then increments each parameter one at a time by a specified amount until the predicted fire variables increase by 10, 20, 30, 40, and 50% of their baseline value, or until the parameter exceeds its limiting values. Limiting values were imposed on the parameters to prevent ridiculous increases in parameters and to save computer run time and costs. The parameter increments and limiting values are given in Table 5. As each fire variable percent level is reached, the absolute value and percent change in the input parameter is listed.

While the program evaluates and outputs model sensitivity based upon nine fire variables, further discussion and analysis will deal only with a single indicator variable, the total fireline intensity (I_B). Not only will this simplify the following discussion, it will also reduce certain redundancies in examining all the variables. The I_B is a good indicator of the other eight variables as it requires the reaction intensities and

residence times of all three strata as well as the R_{max} in its computation. This relationship is linear. The fireline intensity also serves as the independent variable in calculating flame lengths and scorch heights.

In selecting an acceptable level of change in the total fireline intensity for testing the parameter effects, the range of basline I_B values for the twelve hypothetical fuel models were examined. These values range from 26.37 kcal/m-s (Model 4) to 298.1 kcal/m-s (Model 12). The effects of increasing these values by 10, 20, 30, 40, and 50% were examined in terms of the resulting changes in R_{max}, flame length, and scorch height. It was felt that a 10% error (approximately 2.5-30 kcal/m-s) would be the most acceptable over all the fuel conditions tested. This reflects a resolution of 0.26 to 1.19 kilometers per day in the maximum fire spread rate, of 0.03 to 0.09 meters in flame length, and 0.22 to 1.13 meters in scorch height over all twelve models (Table 6).

RESULTS

The results of the programmed analyses are summarized in Table 7. The table lists, by model, the absolute change in the parameters' initial values necessary to affect an increase in the total fireline intensity by ten percent. These values may be interpreted as the amount of absolute error allowable in the assessment of each parameter to retain an error of less than ± 10% in the prediction of the fireline intensity for that fuel condition.

DISCUSSION

An examination of Table 7 demonstrates the complex nature of the fire model's relationships, the dependence of its sensitivity upon the initial values of the input parameters, and the interaction between the eight fuel components as a result of the surface area weighting method.

Models 1 and 2 generally represent range or agricultural lands with their heavy loads of grass and herbs and little or no fallen branchwood. Fire spreads rapidly through these arrays, accounting for the high I_B in the absence of woody fuels. The sensitivity of the fire model to these grass fuels is quite high; a 30 gm/m^2 (5-6%) increase in mass affecting a 10% increase in the total fireline intensity. Similarly, a drop in the grass and herb fuel moisture from 3.0% to 2.5% also increases the I_B by ten percent. This translates as an increase in fire spread by about one kilometer per day under a two mi/h wind.

Due to the linear relationship between fire spread rate and fireline intensity, and the fact that fire spreads very rapidly through grass fuels, it would take significant quantities of dead and down or shrub fuels to increase the I_B by ten percent. If these required quantities were added, the fuel array could no longer be considered as representative of a rangeland condition.

Models 3, 4, and 5 may represent either open savannah lands or young maturing forests with moderate loads for all fuel components. These arrays still show a marked sensitivity to grass and herb loads, as well as high sensitivities to shrub foliage (which is at 2.0 to 4.0 T/ha). Fire

model sensitivity to the woody branchwood fuels decrease as the components' surface-area-to-volume ratio decreases. This is expected since the individual fuels' effects upon fire behavior is weighted by their contribution to the array's total surface area. Thus the sensitivity is not only a function of the particle's size, but also its total volume. This explains the fire model's equal sensitivity to the 2.55-7.62 cm and greater than 7.62 cm fuels; while the >7.62 cm fuel has a surface-area-to-volume ratio one-third that of the 2.55-7.62 cm fuels, it typically has more than three times the volume in natural fuel beds. In fact, for Models 3 through 12, the largest fuels are accumulating at a higher rate than the 2.55-7.62 cm fuels, resulting in increased sensitivity to them.

Models 5 through 12 represent increasing accumulations in dead and down fuels with decreasing proportional contributions by the grasses, herbs, and shrubs. It may therefore be viewed as a progression from a young, open forest to a decadent, closed-canopy stand. Due to the successively heavier accumulations of fuels greater than 7.62 cm in diameter, the fire model's sensitivity to all the other fuel components steadily decreases.

Sensitivity to litter loads decreases from Models 4 through 12 as more and more litter must be ignited to overcome the increasing I_B due to large fuels. This trend is also found for the shrub fuels.

The fire model appears to be sensitive only to the grass and herb fuel moisture contents. This can be attributed not only to this fuel's high surface-area-to-volume ratio, but also to the initial moisture values of the other fuel components. Had more moist conditions been used a sensitivity to these other fuels' moistures may have been found.

Sensitivity to packing ratios is fairly constant within each stratum over all fuel models. The litter packing ratio sensitivity ranges from .0055 to .0102. This is more easily interpreted as a sensitivity to changes in the measured litter depth of 0.2 to 0.4 cm. The packing ratio ranges for the dead and down fuel stratum is quite narrow, .0006 to .0007, which is equivalent to a 1.0-2.0 cm change in bed depth. Finally, the shrub stratum packing ratio sensitivity varies from .0009 for light loads to .0125 for heavy loads, or a sensitivity of 7.0 to 8.0 cm in shrub depth.

This high fire model sensitivity to packing ratio and bed depth is not unexpected as many of the model's intermediate equations use these values as parameters.

The model's sensitivity to windspeed is fairly constant over all fuel conditions in the analysis. This sensitivity to a 0.2 mi/h change at mid-flame height corresponds to a 0.5 to 1.5 mi/h change at 20 feet, Finally, the model's sensitivity to the terrain slope slightly decreases from 2.2° to 28° (4-5%) as the total load increases.

CONCLUSIONS AND RECOMMENDATIONS

Using the twelve hypothetical fuel models as representative of three general fuel conditions--grassland/agricultural, savannah/krummholz/young forest, and old forest/harvested stands--some broad guidelines for parameter assessment accuracies were selected (Table 8). Note that these are only preliminary guidelines based upon general fuel conditions at specific moisture and wind levels.

This analysis is not intended as a definitive study in inventory

accuracy requirements for use with a fire model, but rather a demonstration of how these accuracy requirements change between fuel, weather, and site conditions. That is, the range, timber, and slash managers must each be concerned with different sampling error tolerances for their individual situations.

If a manager intends on conducting any major inventory whose results may be used as inputs into a fire model, it is highly recommended he repeat the procedure outlined here. The computer programs to perform the data conversions and sensitivity analyses have been constructed, tested, documented, and stored in USDA Forest Service files. All the managers need do is conduct a preliminary inventory on a few (2-4) fuel conditions representative of the range of situations on his district. These preliminary results can then be used for a more specific sensitivity analysis yielding error tolerances for further sampling "fine-tuned" to his area. Furthermore, he will have the option of selecting moisture conditions, fire variables, and tolerance levels of greatest importance to him for the analysis.

With a knowledge of his sampling error tolerances and the variances of the preliminary inventory data, the manager now has guidelines for the number of samples required in each stand, and can determine manpower and time allotments. If these requirements are too high, he may wish to have the analysis repeated at a higher error tolerance level.

The result of this effort is a well designed set of field sampling error tolerances. These tolerances assure the manager that the data collected within these guidelines are of high enough accuracy as to satisfy his error requirements of state-of-the-art fire models.

TABLE 1

ROTHERMEL FIRE MODEL INPUTS

Mean values of j^{th} fuel component in i^{th} stratum:

$(W_o)ij$ = ovendry loading, (metric tons 1 hectare)

$(\sigma)ij$ = surface-area-to-volume ratio, (1/cm)

$(S_T)ij$ = mineral content, (gm minerals/gm wood)

$(S_e)ij$ = effective mineral content, (gm minerals - gm silica)/gm wood

$(h)ij$ = low heat value, (kcal/gm)

$(M_f)ij$ = moisture content, (gm moisture/gm ovendry wood)

$(P_p)ij$ = ovendry particle density, (gm/cm^3).

Mean value of i^{th} stratum:

$(M_x)i$ = moisture content of extinction, (gm moisture/gm wood)

$(B)i$ = stratum packing ratio, (dimensionless).

Mean fuel array properties:

$\emptyset$ = slope, (degrees)

U = wind velocity at midflame height, (mph)

m = total number of strata

n = number of fuel components with i^{th} stratum.

TABLE 2: INITIAL VALUES OF TESTED FIRE MODEL PARAMETERS FOR 12 HYPOTHETICAL FUEL CONDITIONS

FUEL PARAMETERS

MODEL	METRIC TONS PER HECTARE								PACKING RATIO		
							- SHRUB -				
No.	LITTER	GRASS	1 HR.	10 HR.	100 HR.	>100 HR.	FOL.	STEM	1	2	3
1	5.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0	.0500	.0050	.0024
2	5.0	4.0	1.0	1.0	0.0	0.0	1.0	2.0	.0500	.0060	.0024
3	5.0	3.0	1.5	2.0	2.0	10.0	2.0	4.0	.0500	.0085	.0024
4	5.0	2.0	2.0	3.0	4.0	20.0	3.0	9.0	.0500	.0100	.0048
5	5.0	2.0	2.5	4.0	6.0	30.0	4.0	16.0	.0500	.0105	.0080
6	5.0	2.0	3.0	5.0	8.0	40.0	5.0	25.0	.0500	.0110	.0120
7	5.0	2.0	3.5	6.0	10.0	50.0	6.0	36.0	.0500	.0115	.0168
8	6.0	2.0	4.0	7.0	12.0	60.0	5.0	25.0	.0500	.0120	.0120
9	7.0	2.0	4.5	8.0	14.0	70.0	4.0	16.0	.0500	.0125	.0080
10	8.0	2.0	5.0	9.0	16.0	80.0	3.0	9.0	.0500	.0130	.0048
11	9.0	2.0	5.5	10.0	18.0	90.0	2.0	4.0	.0500	.0135	.0024
12	10.0	2.0	6.0	11.0	20.0	100.0	1.0	2.0	.0500	.0140	.0024
Moisture	3.0	3.0	3.0	5.0	13.0	16.0	3.0	100.0			

Slope=10° (17.6%)   Wind=0.90 m/s (20 mph)   Temp.=25°C

TABLE 3: VALUES OF CONSTANT FIRE MODEL PARAMETERS FOR 12 HYPOTHETICAL FUEL CONDITIONS

PARAM	UNITS	LITTER	HERBS	Fallen Branchwood 1 HR.	Fallen Branchwood 10 HR.	Fallen Branchwood 100 HR.	Fallen Branchwood >100 HR.	SHRUB FOLIAGE	SHRUB STEMWOOD
h	kcal/gm	4778	4444	4833	4778	4778	4778	4222	4222
σ	1/cm	86.94	131.23	14.76	3.28	0.98	0.33	141.1	14.76
Pp	gm/cc	0.55	0.46	0.58	0.50	0.50	0.50	0.46	0.51
Se	fraction	.020	.014	.002	.002	.002	.002	.002	,003
S_T	fraction	.035	.053	.002	002	.002	.002	.052	.052
M_x	fraction	0.40	0.17	0.17	0.17	0.17	0.17	0.15	0.15

TABLE 4: INITIAL VALUES OF EIGHT FIRE BEHAVIOR CHARACTERISTICS FOR 12 HYPOTHETICAL FUEL CONDITIONS

Model	Meters/ Minute			kcal/M-S	Meters			
No.	R_1*	R_2	R_3	I_R	FL_1	FL_2	FL_3	SH3
1	0.39	8.29	0.00	164.6	0.21	1.36	0.00	10.13
2	0.39	5.34	1.00	93.4	0.21	1.00	0.12	6.84
3	0.39	2.78	2.00	42.1	0.21	0.65	0.22	3.86
4	0.39	1.84	1.46	26.4	0.21	0.50	0.23	2.72
5	0.39	2.14	1.13	35.6	0.21	0.59	0.22	3.42
6	0.39	2.53	0.89	49.4	0.21	0.72	0.20	4.15
7	0.39	2.97	0.71	68.4	0.21	0.88	0.18	5.49
8	0.47	3.46	0.89	97.7	0.25	1.05	0.20	7.06
9	0.54	3.96	1.13	134.7	0.28	1.23	0.22	8.82
10	0.62	4.48	1.46	179.7	0.32	1.43	0.23	10.76
11	0.70	4.99	2.00	233.2	0.36	1.63	0.22	12.85
12	0.78	5.50	1.00	295.6	0.40	1.84	0.12	15.10

*1 = Litter Stratum
2 = Dead and Down Stratum
3 = Shrub Stratum

TABLE 5 = LIMITING AND INCREMENT VALUES FOR FIRE MODEL INPUT PARAMETERS

PARAMETER	UNITS	INCREMENT	LIMIT
Windspeed	mph	0.10	15.0
Slope	degrees	0.10	70.0
Temperature	^{o}C	0.10	35.0
Litter Load	T/ha	0.05	20.0
Grass & Herb Load	T/ha	0.05	20.0
1 hr. load	T/ha	0.05	15.0
10 hr. load	T/ha	0.05	25.0
100 hr. load	T/ha	0.10	50.0
>100 hr. load	T/ha	0.10	250.0
Shrub Fol. load	T/ha	0.05	50.0
Shrub Stem load	T/ha	0.10	100.0
Litter Moisture	% odw	-0.10	0.0
Herb Moisture	% odw	-0.10	0.0
1 hr. moisture	% odw	-0.10	0.0
10 hr. moisture	% odw	-0.10	0.0
100 hr. moisture	% odw	-0.10	0.0
>100 hr. moisture	% odw	-0.10	0.0
Litter packing ratio	dimensionless	-0.0001	0.0
Dead & down packing ratio	dimensionless	-0.0001	0.0
Shrub Packing ratio	dimensionless	-0.0001	0.0

TABLE 6: EFFECTS OF 10 PERCENT INCREASE IN FIRELINE INTENSITY ON THREE FIRE BEHAVIOR CHARACTERISTICS FOR 12 HYPOTHETICAL FUEL CONDITIONS

MODEL NUMBER	INITIAL I_B kcal/m-s	Δ R max km/day	Δ FL max meters	Δ SH3 meters
1	164.63	1.19	0.07	0.76
2	95.82	0.77	0.05	0.52
3	42.05	0.40	0.04	0.31
4	26.37	0.26	0.03	0.22
5	35.63	0.31	0.03	0.27
6	49.41	0.36	0.04	0.34
7	68.35	0.43	0.05	0.42
8	103.19	0.50	0.06	0.54
9	140.65	0.57	0.06	0.67
10	185.48	0.65	0.07	0.81
11	237.82	0.72	0.08	0.96
12	298.14	0.79	0.09	1.13

TABLE 7

ABSOLUTE CHANGE IN FIRE MODEL PARAMETERS NECESSARY TO AFFECT A TEN PERCENT INCREASE IN FIRELINE INTENSITY FOR 12 HYPOTHETICAL FUEL CONDITIONS

	PARAM.*	Model Number 1	2	3	4	5	6	7	8	9	10	11	12
	Wind	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
	Slope	2.20	2.20	2.40	2.50	2.50	2.60	2,60	2.70	2.70	2.70	2.80	2.80
Fuel Loads T/ha	Litter	1.90	1.65	1.45	1.35	1.60	1.85	2.20	2.70	3.25	3.80	4.45	5.15
	Grass & Herbs	0.30	0.25	0.20	0.25	0.45	0.90	1.80	3.00	4.45	6.10	7.95	9.95
	0.0-0.64 cm	6.60	4.10	2.45	1.35	1.40	1.50	1.70	1.95	2.30	2.60	2.90	3.25
	0.65-2.54 cm	9.60	6.75	4.15	2.35	2.35	2.45	2.60	2.90	3.20	3.45	3.75	5.00
	2.55-7.62 cm	17.60	14.3	9.00	5.10	4.80	4.90	5.10	5.40	5.90	6.30	6.70	7.20
	>7.62	28.50	23.2	9.90	3.80	3.30	3.20	3.20	3.40	3.60	3.90	4.10	4.40
	Shrub. Fol.	2.50	2.2	0.90	0.95	2.40	3.20	4.55	4.60	4.75	5.15	3.05	4.35
Fuel Moistures, %	Grass & Herbs	-0.5	-0.5	-0.6	-0.7	-0.7	-0.7	-0.7	-0.8	-0.8	-0.9	-0.9	-0.9
	>7.62 cm	>16.	>16.	>16,	>16.	>16.	>16.	-15.8	-14.1	-12.9	-11.9	-11.2	-10.7
	Shrub. Fol.	>3.	>3.	-2.8	-2.4	>3.	>3.	>3.	>3.	>3.	>3.	>3.	>3.
	Shrub Branchwood	>100.	-94.1	-85.1	-85.1	-85.1	-85.1	-85.1	-85.1	-85.1	-85.1	>100.	>100.
Packing Ratios	Litter	.0102	.0066	.0058	.0055	.0063	.0072	.0083	.0085	.0087	.0089	.0092	.0094
	Dead & Down	.0007	.0006	.0007	.0008	.0008	.0009	.0009	.0009	.0009	.0009	.0009	.0009
	Shrub	>.0024	.0021	.0009	.0014	.0041	.0079	.0125	.0090	.0059	.0034	.0016	.0021

*Parameters not listed exceeded their maximum value for all fuel models without changing the predicted I_B by 10% of its initial value.

TABLE 8: SUGGESTED GUIDELINES OF SAMPLING ERROR TOLERANCE FOR THREE FUEL CONDITIONS

PARAMETER	ERROR RANGE	RECOMMENDED GRASSLAND	ERROR SAVANNAH	TOLERANCES FOREST
Wind (mph)	0.2	1	1	1
Slope (degrees)	2.2-2.8	2	2	2
Litter (T/ha)	1.35-5.15	1.5	1.5	2.0
Grass (T/ha)	0.20-9.95	0.25	0.25	1.0
1 HR (T/ha)	1.35-3.25	-	1.0	1.5
10 HR (T/ha)	2.35-9.60	-	2.0	2.5
100 HR (T/ha)	4.80-17.60	-	4.0	5.0
>100 HR (T/ha)	3.20-28.5	-	3.0	3.0
Shrub Foliage(T/ha)	0.90-5.15	1.0	1.0	4.0
Grass Moisture (%)	0.5-0.9	0.5	0.5	0.5
Litter Depth (cm)	0.2-0.4	0.2	0.3	0.4
Dead and Down Depth	2.0	2.0	2.0	2.0
Shrub Depth (cm)	7.0-8.0	7.0	7.0	7.0

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APPENDIX

PROGRAM CONTROL AND INPUT FOR "SANAL" OK

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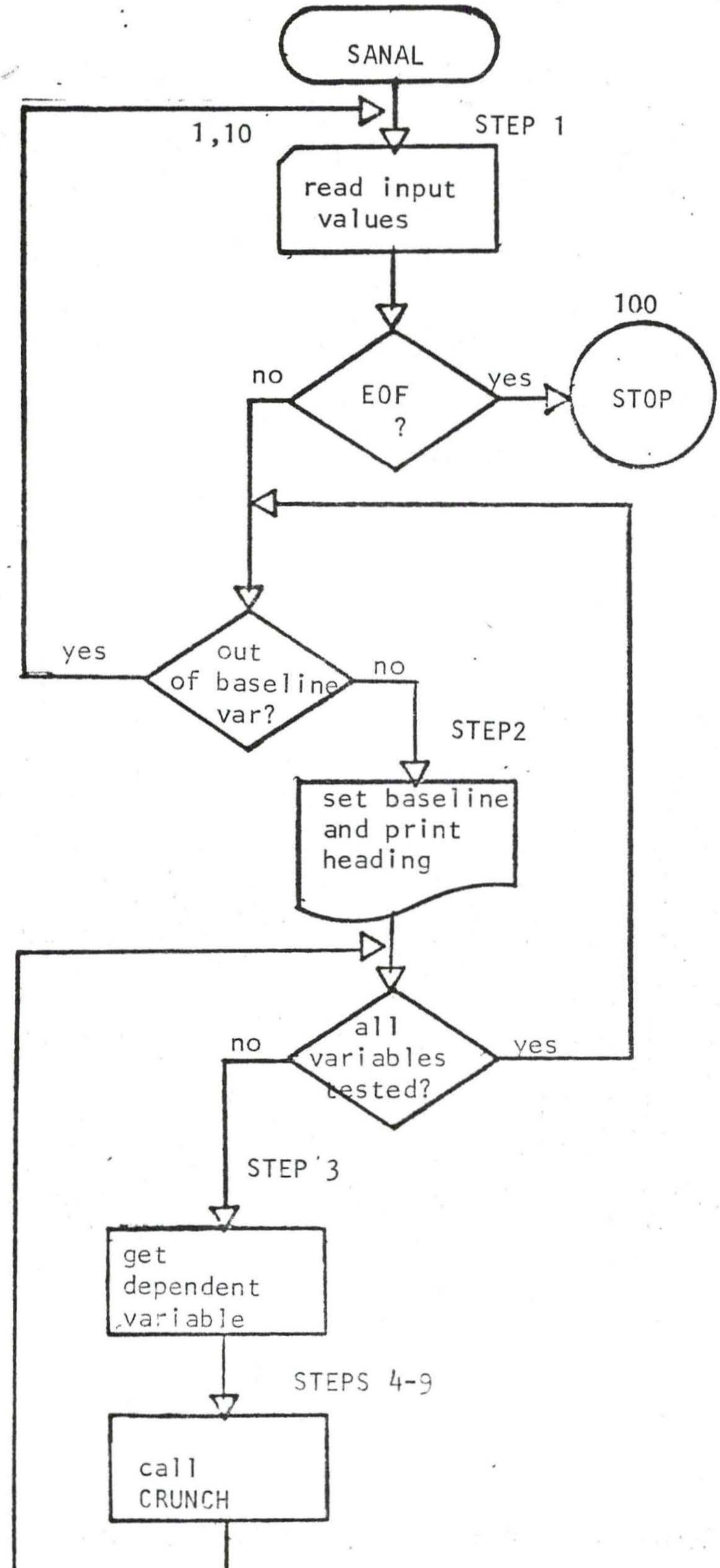
SEN,7,150,150000.803645,2108-IGMI BEVINS
LIBCOPY,GMI,SANAL,SANAL.
FETCHPS,MNF,MNF,OLDMNF.
MNF,I=SANAL.
LINK,X.
DISPOSE,OUTPUT=PR,SC=FL.
EOR
SAMPLE INPUT DATA
100.0                    PERCENT LITTER COVER
100.0                    PERCENT DEAD AND DOWN COVER
100.0                    PERCENT SHRUB COVER
100.0                    PERCENT CURED GRASSES AND HERBS
 40.0                    PERCENT CURED SHRUB FOLIAGE
300.0                    FUEL MOISTURE, LIVE GRASSES AND HERBS
300.0                    FUEL MOISTURE, LIVE SHRUB FOLIAGE
  2.0                    WINDSPEED AT MIDFLAME HEIGHT (MPH)
 10.0                    TERRAIN SLOPE (DEGREES)
 25.0                    AMBIENT TEMPERATURE (CELCIUS)
  5.0                    LITTER LOAD (METRIC TONS/HECTARE)
  2.0                    GRASS AND HERB LOAD (T/HA)
  2.0                    1 HR LOAD (T/HA)
  4.0                    10 HR LOAD (T/HA)
  8.0                    100 HR LOAD (T/HA)
 40.0                    >100 HR LOAD (T/HA)
  4.0                    SHRUB FOLIAGE LOAD (T/HA)
 20.0                    SHRUB STEMWOOD LOAD (T/HA)
  5.0                    LITTER MOISTURE (%)
  3.0                    DEAD GRASS AND HERB MOISTURE (%)
  4.0                    1 HR MOISTURE (%)
  5.0                    10 HR MOISTURE (%)
  8.0                    100 HR MOISTURE (%)
 12.0                    >100 HR MOISTURE (%)
  3.0                    DEAD SHRUB FOLIAGE MOISTURE (%)
100.0                    SHRUB STEMWOOD MOISTURE (%)
0.0500                   LITTER PACKING RATIO
0.0150                   DEAD AND DOWN PACKING RATIO
0.0100                   SHRUB PACKING RATIO
```

FLOWCHART FOR SANAL ROUTINE :



FLOWCHART FOR CRUNCH SUBROUTINE